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CONCLUDING REPORT

6 ARPA BIOCYBERNETICS PROJECT

Concluding Report

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## INTRODUCTION

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→ ~~Our~~ <sup>THE</sup> objective in the DARPA Biocybernetics Program was to investigate the use of pupillary responses in assessing attentional demands on operators of complex man-machine systems. The results of this project were strongly positive; the task-evoked pupillary response has emerged as an excellent physiological indicator of mental workload. ↙

The major findings of this project are summarized in the remainder of this final report.

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PREDICTION OF DETECTION OF WEAK ACOUSTIC SIGNALS FROM  
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## INTRODUCTION

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The iris of the eye is a complex mechanical structure, composed of two opposing muscle groups, the sphincter and dilator pupillae, that are respectively innervated by the parasympathetic and sympathetic branches of the autonomic nervous system (Lowenfeld, 1958). Pupillary diameter is determined by the momentary state of activation of these two muscular tissues. That the pupil is reactive to a variety of covert cognitive processes suggests that these mental events are reflected in important ways onto the autonomic periphery. For this reason, the analysis of pupillary movements provides an important tool for the study and prediction of internal cognitive events (Goldwater, 1972).

This paper briefly outlines the mechanism underlying the pupillary response to suprathreshold sensory stimuli as determined from investigations on infrahuman species, summarizes the sparse literature relating pupillary change to perceptual events in man, proposes a method of relating pre-response pupillary movements to the prediction of the outcome of a sensory decision process in man, and presents some experimental data testing the utility of pupillometric data in the prediction of behavioral response on a single-trial basis.

A wide variety of published reports have demonstrated strong and orderly relationships between pupillary dilation and cognitive processing in short- (Kahneman & Beatty, 1966) and long-term (Beatty & Kahneman, 1966) memory tasks, during mental multiplication (Hess & Polt, 1964) and problem solving (Bradshaw, 1968), while constructing a visual image of verbally presented material (Simpson & Paivio, 1966, 1968), in perceptual discrimination (Kahneman & Beatty, 1967) and detection (Hakerem & Sutton, 1966) experiments, and in other information-processing tasks (Goldwater, 1972).

While little can be known of the detailed anatomical mechanisms mediating these pupillary changes during human cognitive processing, an examination of a related phenomenon, the "sensory reflex", that may be observed in a wide variety of vertebrates including man may be instructive. A robust and reliable pupillary dilation may be obtained in response to the presentation of a sensory stimulus of moderate intensity in any of the sensory modalities, a response that physiologists have termed the "sensory reflex" and employ as a sign of the integrity of the thalamocortical system in acute preparations. In a detailed historical and experimental analysis, Lowenfeld (1958) concludes that the pattern of pupillary change is controlled by diencephalic brain mechanisms with cortical input and executed through



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lower portions of the autonomic nervous system. The response is of short latency, occurring within 300-500 msec following stimulation. This short-latency component is mediated directly by sympathetic input to the dilator pupillae. Lesion of the sympathetic ganglia abolishes the short-latency component of the dilation, but a slower, less extensive dilation may still be observed. This later component results from central inhibition of the third nerve nucleus which parasympathetically innervates the sphincter pupillae. Thus it appears that the simple processing of sensory information not only produces detectable changes in the pattern of ongoing cortical activity (see Regan, 1972; Shagass, 1972, for reviews) but results in significant changes in the activity of autonomic nervous system that is observable in the periphery.

In man, the magnitude of the pupillary response to a sensory stimulus varies as a function of the meaning of the stimulus and the nature of cognitive processing that occurs. For example, Kahneman and Beatty (1967) have reported that pupillary dilation is larger to high information signals than to low information stimuli in a pitch discrimination task. Further, the magnitude of dilation is greater for difficult than for easy discriminations.

Hakerem and Sutton (1966) have investigated the averaged pupillary response to weak visual stimuli, and conclude that a large pupillary dilation may be observed for correctly detected signals whereas the response to missed signals was greatly attenuated or absent. While numerous difficulties trouble that experiment (the use of visual signals, the infrequent use of blank trials, the use of differential response procedures and the lack of conventional statistical analysis) these results are instructive. Such data suggest that the presence of a pupillary dilation to a weak sensory stimulus may serve as a physiological sign of cognitive processing of a stimulus, and thus provide the investigator with a psychophysiological measure of successful perceptual detection of weak signals. Hakerem and Sutton present only averaged data and therefore provide no direct evidence concerning the utility of pupillometric measurement of ongoing cognitive processes in man.

To provide a more direct test of the relationship between pupillary movements and ongoing cognitive processes in man, an experiment similar to that of Hakerem and Sutton (1966) was performed. To avoid the confounding effects of the light reflex to visual stimuli in studying higher cognitive processes in perception, acoustic stimuli were employed. To adequately control for the effects of decision variables in the perception of weak signals, the probability of signal presentation on any trial was re-

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duced to .50 and procedures derived from signal detection theory (Green & Swets, 1966) were employed in data analysis. To prevent the confounding of cognitive and response variables, the subject was required to indicate either decision outcome by the movement of a response lever. Finally, to permit an assessment of the stability of the pupillary response to individual signals, single trial behavioral and pupillary data were stored on disk for later analysis.

The purpose of the present experiment was therefore to determine if the outcome of the human decision process involved in the detection of low-level sensory signals can be predicted from an analysis of the pupillary movement occurring between signal presentation and response initiation.

#### **METHOD**

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Five university students served as volunteer subjects. Using a yes/no signal-detection paradigm (Green & Swets, 1966) subjects attempted to detect the presence of a 100-msec, 1 kHz tone burst against a continuous white noise (0-2.6 kHz) background. Trials were unsignalled and indicated only by the response cue, a 1-sec suppression of the background noise, which occurred exactly 2 sec after presentation of the signal on trials. Following the response cue the subject rendered his decision by moving the response switch in either the "yes" or the "no" direction. Each experimental run consisted of 32 single trials, half of which contained a signal. Inter-trial intervals ranged randomly between 15 and 55 secs; since no warning signal was employed, the subjects were required to continuously monitor the background noise for the presentation of a signal. The intensity of the signal was adjusted individually for each subject to yield a probability of correct response of approximately .75. Subjects were given several practice trial blocks following which an experimental run was made with concurrent pupillary measurement.

Acoustic stimuli were generated under computer control using standard psychoacoustic procedures (Green & Swets, 1966). Acoustic white noise was obtained from a Hewlett-Packard 8057A Precision Noise Generator, externally clocked to yield an output spectrum that was flat from DC and 3 db down at 2.6 kHz. A 100 msec 1,000 Hz tone burst was generated by a Hewlett-Packard 200AB Audio Oscillator capacitatively filtered to eliminate onset and offset clicks. Noise and signal output were mixed with a linear operational amplifier system, amplified by a McIntosh 75 Power Amplifier and presented to the subject through binaural Koss Pro 5LC headphones.

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Pupillary diameter was measured using a Whittaker Series 1000 TV Pupillometer, the analog output of which was available at the instrumentation interface of the computer. During the experimental run, each subject viewed a 3 mm black fixation point placed upon a white field at a distance of 6 m. Illumination of the field was 22 footlamberts.

The conduct of the experiment and the analysis of all data was accomplished with a Hewlett-Packard 2116B laboratory computer system. During data acquisition, the computer controlled the delivery and duration of stimuli, obtained data from the pupillometer, displayed both behavioral and pupillary data to the experimenter as a check for artifacts, and stored all accepted data on disk for later analysis. Pupillary data was obtained at a 20 msec sample rate for the 5 sec preceding the response signal. Individual trials were rejected if a blink appeared in the pupillary record between signal presentation and response cue.

## RESULTS

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An examination of the averaged pupillary responses for those trials in which a signal was actually presented demonstrates the close relationship between pupillary movements and perceptual events. Figure 1 presents these responses for correctly detected and missed signals averaged over all five subjects. It can be seen that the rather large dilation following signal presentation for hits is either severely attenuated or absent in the averages for detection failures. This differentiation of pupillary response by response type is quite reliable and significant by a sign test ( $p < .05$ ). Thus the relationship between pupillary dilation and successful detection originally observed by Hakerem and Sutton (1966) for visual signals holds for acoustic signals as well.

The consistency of this relationship within each individual subject may be estimated by attempting to use the pattern of pupillary movements between signal presentation and the onset of the response cue to predict the behavioral performance of the listener. To accomplish this objective, the following analysis was performed.

For a given subject all trials on which a signal had been presented were selected for analysis and divided into two groups on the basis of the listener's decision. An attempt was made to determine to which of these groups, the hits or the misses, an individual trial belonged by computing the averaged response for hits and the averaged response for misses, with the individual trial being tested removed from these averages. The corre-

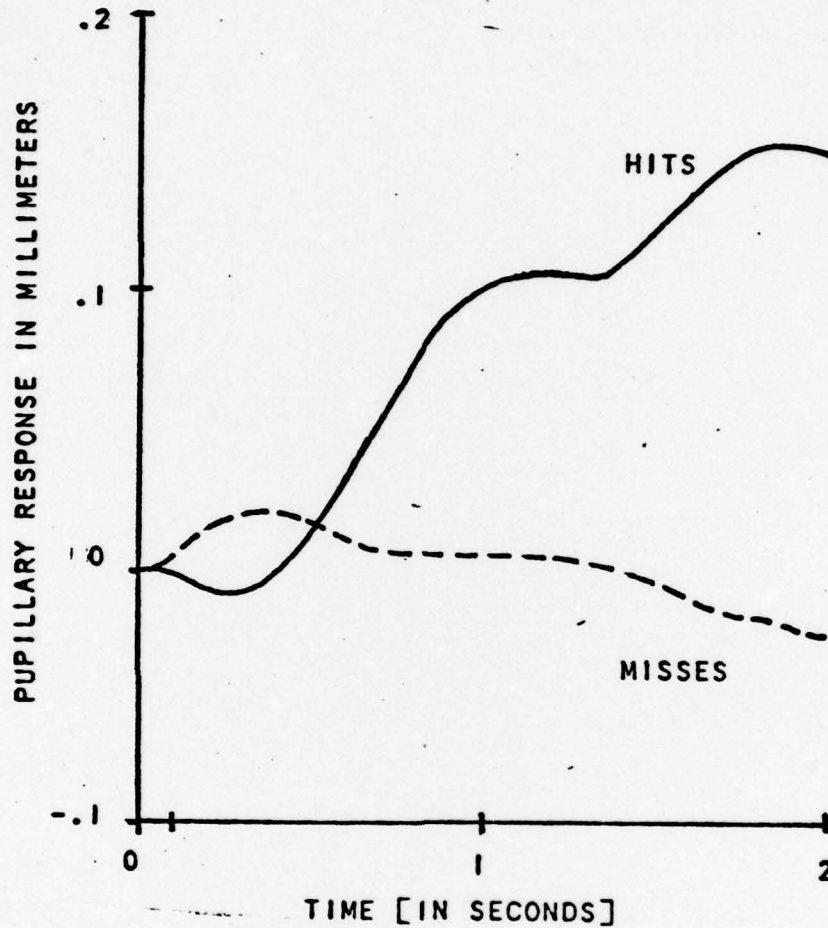
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FIGURE 1

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Averaged pupillary responses for the five listeners for hits and misses in the 2 second period following signal presentation. Signal duration is 100 msec and signal offset is indicated on the graph.

lations between the individual trial and the averaged hit response and the averaged miss response were then computed and a ratio of these two correlations was then formed:

$$R = \left( \frac{1 + r_{\text{trial}/\text{hits}}}{1 + r_{\text{trial}/\text{miss}}} \right) - 1$$

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This ratio was used as an index of waveshape correspondence between a single trial and the two averaged responses that are based upon the remaining data. This procedure is similar to the cross-validation method outlined by Mosteller and Tukey (1968) and has the advantage of permitting  $N$  independent validation tests based upon estimators computed from  $(N-1)$  observations, where  $N$  is the number of trials. The process of estimator construction and prediction is repeated for each of the  $N$  trials.

This procedure successfully predicted 92 percent of the decisions of subject LP, 81 percent for subject JS, 73 percent for subjects JB and SA, and 66 percent for subject BW. The success of prediction appears to be in large part a function of the averaged degree of correlation between the averaged response to hits and misses, the power of prediction increasing when the waveshape of the averaged responses are more highly differentiated. These predictions differ significantly from chance levels by a Fisher test of exact probabilities for subjects LP ( $p < .005$ ), JS ( $p < .02$ ), JB and SA ( $p < .10$ ), but not for BW ( $p < .20$ ), if a two-tailed criterion is employed.

#### DISCUSSION

These data are of some practical consequence in that they demonstrate the possibility of reliably ascertaining the outcome of a cognitive process preceding behavioral indications through the measurement of a concomitant physiological response, here the pattern of pupillary movement in the period following presentation of the signal and before the initiation of behavioral responding. But by no means should the performance of the predictor process here employed be regarded as optimal. First a predictor generated from a larger data base might be more reliable, in that error variance in the estimation of the predictors themselves would be reduced. Second the prediction algorithm employed in the present study utilized only waveshape information in discriminating response categories and ignored completely the magnitude of the response. Since the amplitude of the averaged dilations to hits and misses differ markedly, an amplitude-sensitive decision rule might be expected to yield improved performance. Finally, improved prediction might result when the performance of highly practiced subjects is tested, since increased behavioral stability should reduce the variance of the autonomic signs of cognitive functioning.

Further, these data are of theoretical interest as well. They both extend the previous observations of Hakerem and Sutton (1966) to the perception of weak non-visual signals and demonstrate the highly reliable nature of the peripheral autonomic reflection of cognitive processes. Thus the de-

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monstration that one might predict the outcome of a perceptual decision process on the basis of pupillary measurement also suggests that such autonomic events are a stable and constant component of the perceptual decision processes. Further, these peripheral signs of sympathetic activation occur at latencies similar to those reported for brain wave signs of decision processes in man. This coincidence suggests the existence of a process occurring in close temporal association with critical cognitive processes and observable throughout the neuraxis that is intimately related to the momentary state of the information-processing systems of the brain.

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#### REFERENCES

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- Beatty, J., & Kahneman, D. Pupillary changes in two memory tasks. Psychonomic Science, 1966, 5, 371-372.
- Bradshaw, J. L. Pupil size and problem solving. Quarterly Journal of Experimental Psychology, 1968, 20, 116-122.
- Goldwater, B. C. Psychological significance of pupillary movements. Psychological Bulletin, 1972, 77, 340-355.
- Green, D. M., & Swets, J. A. Signal detection theory and psychophysics. New York: Wiley, 1966.
- Hakerem, G., & Sutton, S. Pupillary response at visual threshold. Nature, 1966, 212, 485-486.
- Hess, E. H., & Polt, J. M. Pupil size in relation to mental activity during simple problem-solving. Science, 1964, 143, 1190-1192.
- Kahneman, D., & Beatty, J. Pupil diameter and load on memory. Science, 1966, 154, 1583-1585.
- Kahneman, D., & Beatty, J. Pupillary responses in a pitch-discrimination task. Perception and Psychophysics, 1967, 2, 101-105.
- Lowenfeld, I. E. Mechanisms of reflex dilatation of the pupil. Documenta Ophthalmologica, Vol. XII, 1958.
- Mosteller, F., & Tukey, J. W. Data analysis, including statistics. In G. Lindzey & E. Aronson (Eds.), The handbook of social psychology (2nd ed.) Vol. II. Reading, Mass.: Addison-Wesley, 1968.
- Regan, D. Evoked potentials in psychology, sensory physiology and clinical medicine. New York: Wiley, 1972.
- Shagass, C. Evoked brain potentials in psychiatry. New York: Plenum, 1972.
- Simpson, H. M., & Palvio, A. Changes in pupil size during an imagery task without motor response involvement. Psychonomic Science, 1966, 5, 405-406.
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Simpson, H. M., & Paivio, A. Effects on pupil size of manual and verbal indicators of cognitive task fulfillment. Perception and Psychophysics, 1968, 3, 185-190.

PUPILLOMETRIC SIGNS OF SELECTIVE ATTENTION IN MAN

→ top. III

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## ABSTRACT

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Pupillometric measures have demonstrated the involvement of brainstem activating systems in many types of complex cognitive tasks. The present paper extends this analysis to the study of selective attentional processes in perception. Pupillary dilations reflecting task-evoked activation shifts reliably follow the presentation of background stimuli when a perceptual channel is attended, and are otherwise absent. These results are interpreted in the context of Lindsley's neuropsychology of activation and attention.

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The execution of information-processing functions in the human brain reliably elicits momentary increases in the output of brainstem activation systems, the magnitude of which is a function of the cognitive load imposed by the task (Beatty, 1977; Kahneman, 1973). This relation is true not only for complex, load-demanding processes such as mental arithmetic (Hess & Polt, 1964; Payne, Parry, & Harasymiw, 1968), serial memory (Beatty & Kahneman, 1966; Kahneman & Beatty, 1966; Kahneman, Beatty, & Pollack, 1967), and logical reasoning (Ahern, 1978), but for simpler perceptual processes as well (Kahneman & Beatty, 1967). We have recently demonstrated that signs of small event-related activation increases accompany the visual encoding of letter pairs and that the magnitude of this activation is directly related to the hierarchical level within the cognitive system to which the letter-pair is processed (Beatty & Wagoner, 1978). I now report that activation responses accompanying the processing of sensory stimuli may be controlled by attention.

The idea of activation as a physiological variable related to cognitive processing is a prominent feature of Lindsley's neuropsychology (Lindsley, 1960). As a neurophysiological concept, Lindsley and his coworkers identified activation with electrocortical desynchronization and autonomic arousal in their work on the physiological functions of the brainstem reticular activating system (Moruzzi, 1972). Much of this and more recent work demonstrates quite forcefully that to view activation as a single, unidimensional description of central nervous system arousal is a serious oversimplification: the brainstem activation systems are complex, interdependent and subject to external regulation, particularly from telencephalic structures (Schlag, 1974). Nonetheless, a simplified concept of activation has proven to be of heuristic value in exploring the dynamics of complex information processing in the human brain.



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Of the several available methods for measuring CNS activation in man, perhaps the most sensitive and reliable is the measurement of sympathetic and parasympathetic activity as reflected in pupillary diameter (Goldwater, 1972). Further, pupillometric measures have shown a striking correspondence to electrophysiological indices of activation in a long series of studies on corticoreticular interactions (Moruzzi, 1972). Pupillary dilations indicative of CNS activation may be mediated by either increased forebrain inhibition of the Edinger-Westphal nuclei or increased sympathetic discharge (Loewenstein & Loewenfeld, 1952). Orderly relations between pupillary dilation and presumed cognitive load have been reported for a wide variety of cognitive tasks (Hess & Polt, 1964; Payne, Parry, & Harasymiw, 1968; Beatty & Kahneman, 1966; Kahneman & Beatty, 1966; Kahneman, Beatty, & Pollack, 1967; Ahern, 1978; Kahneman & Beatty, 1967; Beatty & Wagoner, 1978). Thus a convincing argument may be made that the degree of pupillary dilation observed during the execution of a particular cognitive function is directly proportional to the demands which that function places on the cognitive system.

To test for the effects of attentional processes on pupillometric signs of task-induced activation to sensory stimuli, an experimental procedure similar to that previously reported by Hillyard (Hillyard, Hink, Schwent, & Picton, 1973) was employed. Eight young adults were required to monitor one channel of an auditory display for targets and report them by depressing a microswitch. A series of 50-msec 800 Hz tone bursts were presented to one ear and 1500 Hz tone bursts to the other by earphones. A channel was defined by frequency of the standard tone bursts with the assignment of ear to frequency randomized over subjects. Infrequently presented targets were tone bursts of slightly higher frequency (860 and 1575 for the low and high-frequency channels respectively).

A computer-generated sequence of probabilistic decisions controlled the sequence of stimuli. Every 50 msec a decision was made to present a stimulus with a probability of 0.15. If this decision was positive two additional choices were made: First the stimulus was assigned to the high-frequency channel with probability 0.50, otherwise the low-frequency channel was selected. Second, the standard stimulus was replaced by a signal on the selected channel with probability 0.066. This procedure generated an average of 1 stimulus every 333 msec and 1 target on the attended channel every 10 seconds. The entire experiment was controlled by a general purpose digital computer.

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This complex, probabilistic method of stimulus sequencing was neces-

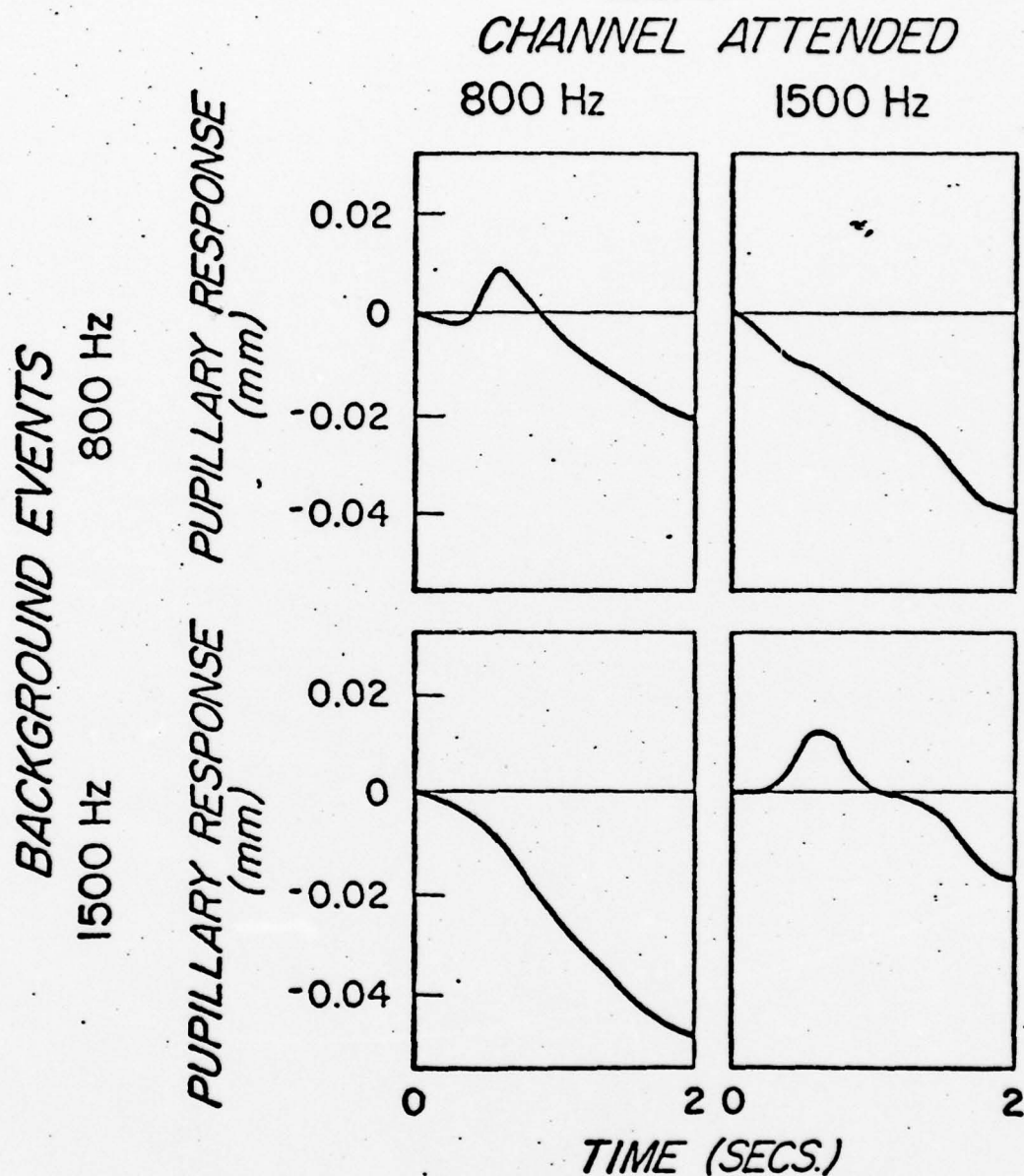
sary to permit unbiased recording of averaged evoked pupillary responses. Pupillary diameter was measured using a Whittaker 1053 TV pupillometer and was digitized at 50 msec intervals. Single evoked pupillary responses were computed to non-target stimuli for a period of 2 sec following stimulus presentation. Thus, on the average, 6 other stimulus events might be expected to occur as the response to any given stimulus was being recorded. To prevent confounding of the pupillometric data, the probability of stimulus presentation must not vary systematically in this period. By completely randomizing the schedule of stimulus presentation, the response to several stimuli could be acquired simultaneously, with each response at different stages of completion. To further reduce artifacts, all data acquired within 2.5 sec preceding either the presentation of a signal or the registration of a detection response was discarded automatically. This control was initiated to remove the large pupillary signs of detection and response initiation from the background monitoring data.

The experiment consisted of 6 blocks of 64 stored 2 sec records obtained according to the described procedure. Four listeners were instructed to detect targets on the high frequency channel in the first 3 blocks and on the low-frequency channel in the last 3 blocks. These instructions were reversed for the remaining listeners.

All behavioral and pupillometric data were stored on disk for later artifact removal and analysis. The pupillometric data from each stimulus were individually inspected for artifacts without knowledge of stimulus type. All trials containing major artifacts were discarded. Trials with small artifacts occurring in non-critical periods were corrected by linear interpolation. For each subject four averaged evoked pupillary responses were then computed for each combination of auditory channel and instructional condition.

Figure 1 presents the group averaged evoked pupillary responses for background events as a function of stimulus channel and attentional instruction. A clear pupillary dilation is present at a latency of about 600 msec following presentation of background stimuli on the attended channel, which is completely absent on the unattended channel. An analysis of variance confirms this observation. The mean amplitude of the pupillary dilation in the 1-sec period following stimulus presentation did not differ significantly between stimulus channels ( $F(1, 7) = 0.60$ ,  $p = .463$ ) nor between attentional instructions ( $F(1, 7) = 1.74$ ,  $p = .229$ ). However, the interaction of stimulus channel and attentional instruction was highly significant ( $F(1, 7) = 11.59$ ,  $p = 0.011$ ). Thus a small pupillary dilation appears following presentation

FIGURE 1



Averaged evoked pupillary responses for 8 subjects in a selective attention experiment. A post stimulus pupillary dilation appears following non-signal stimuli in the channel to which attention is directed and is not present following stimuli in the unattended channel.



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of non-target stimuli when a channel is attended and not otherwise.

Several aspects of these data deserve comment. First, although the event-related pupillary response observed following stimuli on the attended channel is quite reliable and replicable, it is of extremely small magnitude (approximately 0.015 mm). In contrast, the dilation observed under comparable recording conditions for a 6-digit short term memory task is approximately .55 mm. Similarly, mentally multiplying a pair of two-digit numbers such as 13 and 18 results in a dilation of approximately 0.50 mm. If the degree of pupillary dilation evoked by the performance of a cognitive task is proportional to the load imposed by that task on the individual's processing capacity (Beatty, 1977; Kahneman, 1973), then it would appear that the load imposed in processing information from the attended auditory channel is extremely small. In contrast, this same logic leads to the conclusion that the presentation of that stimuli on the unattended channel imposes no measurable load upon the nervous system.

Second, these results are congruent with data previously reported by Hillyard and his colleagues (Hillyard, Hink, Schwent, & Picton, 1973; Hink, Van Voorhis, & Hillyard, 1977) using the same experimental paradigm to study the effects of selective attention on cortical event-related potentials. These authors report that an early (60-70 msec) component of the cortical event-related potential is selectively enhanced for the attended channel and suppressed for the unattended channel. They suggest that the magnitude of this component is indicative of a stimulus set that admits all sensory input to the attended channel for further perceptual analysis. Extending this reasoning, the magnitude of the event-related pupillary response may index the degree to which further capacity-demanding processing is undertaken.

Third, it must be noted that all of the averaged pupillary responses are characterized by a descending baseline. This is probably a consequence of a saw-tooth pattern in the raw data, with large and rapid pupillary dilations following the detection of a target which diminish gradually as a function of time. Since all data surrounding target presentation or detection responses are removed from these averages, the averages presented in Figure 1 are drawn primarily from periods in which the tonic pupillary diameter is slowly decreasing. This property of the data is of little concern, as the short-latency event-related pupillary dilations and the slow baseline changes are of markedly different form.

Finally, these data demonstrate the utility of employing relevant physiological measures in the study of cognitive processing. From a beha-

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violral point of view, they provide a useful converging operation for the analysis of complex mental functions. From a physiological perspective, the data help clarify the dynamics of forebrain-brainstem interactions and the role of activation in cognitive processing. Further, these data lend specific support to the idea that attended stimuli are processed at a capacity-demanding level, but that unattended stimuli are not.

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## REFERENCES

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- Ahern, S.K. Activation and intelligence: Pupillometric correlates of individual differences in cognitive abilities. Unpublished doctoral dissertation, University of California, Los Angeles, 1978.
- Beatty, J. Activation and attention. In M.C. Wittrock, J. Beatty, J.E. Bogen, M.S. Gazzaniga, H.J. Jerison, S.D. Krashen, R.D. Nebes, & T. Teyler, The human brain. Englewood Cliffs, New Jersey: Prentice-Hall, 1977.
- Beatty, J., & Kahneman, D. Pupillary changes in two memory tasks. Psychonomic Science, 1966, 5, 371-372.
- Beatty, J., & Wagoner, B.L. Pupillometric signs of brain activation vary with level of cognitive processing. Science, 1978, 199, 1216-1218.
- Goldwater, B.C. Psychological significance of pupillary movements. Psychological Bulletin, 1972, 77, 340-355.
- Hess, E.H., & Polt, J.H. Pupil size in relation to mental activity during simple problem solving. Science, 1964, 143, 1190-1192.
- Hillyard, S.A., Hink, R.F., Schwent, V.L., & Picton, T.W. Electrical signs of selective attention in the human brain. Science, 1973, 182, 177-180.
- Hink, R.F., Van Voorhis, S.T., & Hillyard, S.A. The division of attention and the human auditory evoked potential. Neuropsychologia, 1977, 15, 597-605.
- Kahneman, D. Attention and effort. Englewood Cliffs, New Jersey: Prentice-Hall, 1973.
- Kahneman, D., & Beatty, J. Pupil diameter and load on memory. Science, 1966, 154, 1583-1585.
- Kahneman, D., & Beatty, J. Pupillary responses in a pitch-discrimination task. Perception & Psychophysics, 1967, 2, 101-105.
- Kahneman, D., Beatty, J., & Pollack, I. Perceptual deficit during a mental task. Science, 1967, 157, 218-219.
- Lindsley, D.B. Attention, consciousness, sleep and wakefulness. In J. Field (Ed.), Handbook of physiology (Vol. III). Washington, D.C.: American

- 
- Physiological Society, 1960.
- Lowenstein, O. , & Loewenfeld, I. E. Disintegration of central autonomic regulation during fatigue and its reintegration by psychosensory controlling mechanisms. I. Disintegration. Pupillographic studies. Journal of Nervous and Mental Disease, 1952, 115, 1-21.
- Moruzzi, G. The sleep-waking cycle. Reviews of physiology: Biochemistry and experimental pharmacology. New York: Springer-Verlag, 1972.
- Payne, D. T. , Parry, M. E. , & Harasymiw, S. J. Percentage pupillary dilation as a measure of item difficulty. Perception & Psychophysics, 1968, 4, 139-143.
- Schlag, J. Reticular influences on thalamo-cortical activity. In O. Creutzfeldt (Ed.), Handbook of Electroencephalography and Clinical Neurophysiology. Volume 2: Electrical activity from the neuron to the EEG and EMG. Amsterdam: Elsevier, 1974.



✓ PUPILLOMETRIC SIGNS OF BRAIN ACTIVATION VARY WITH LEVEL OF  
COGNITIVE PROCESSING, —————→ p. 12

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## ABSTRACT

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The idea that hierarchically higher brain processes require greater amounts of CNS vigilance or activation for their execution was tested in two experiments measuring pupillary dilation during the decision interval of a hierarchically-structured letter-matching task. Larger dilations indicative of increased activation were observed for letter pairs requiring higher levels of processing.

## INTRODUCTION

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Hughlings Jackson (1) in 1884 proposed that functional processes in the human nervous system are hierarchically organized, with the higher levels being increasingly unconstrained or plastic, complex, and voluntary as opposed to automatic. Jackson recognized that factors that reduce CNS vigilance selectively affect the highest levels of integration, an idea which Henry Head later extended in his writings (2). By vigilance was meant the general state of nervous system activation that is now thought to be reflected as electrocortical desynchronization and autonomic arousal (3).

These early investigations studied the level of integration that may be accomplished when the capacity of the nervous system to sustain a normal state of activation has been impaired either by injury, disease or the effects of drugs (2). A modern example of this experimental approach is the discovery that the aphagia and adipsia following lateral hypothalamic lesions are due in large part to a disruption of endogenous activation systems and that with recovery of these systems the hierarchically organized processes governing feeding and drinking return in a Jacksonian sequence of increasing complexity (4). However, it appears that the level of activation in the normal organism is not fixed, but varies from moment to moment and task to task according to the processing demands placed upon the nervous system (5).

This paper reports the results of two experiments that suggest that hierarchically organized cognitive processes vary in the degree to which CNS activation is mobilized during their execution. The cognitive task employed was letter matching, in which a pair of visually-presented upper and/or lower case letters are judged by an observer to be the same or different (6). If a name criterion is employed as in the first experiment, letter-pairs may be judged to be the same if they are orthographically identical (AA) or differ in orthography but share the same name (Aa). Only the physical features of the former pair need be processed before a judgment

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can be reached, whereas the stimuli must be processed at the higher level of naming for the latter type of pair. When a category criterion is used, as in the second experiment, letters are judged same if they belong to a common category, vowels or consonants. In this case a third type of same judgment is introduced in which a physical comparison is made at the lowest level, then the names are extracted, following which membership in a common category is judged (AE or BR). Posner and Mitchell (7) have presented convincing arguments from reaction-time data that the processes of feature analysis, name code extraction and category membership testing are hierarchically organized. In Jackson's (1) terms, matches made at the physical, name and category levels are ordered by increasing plasticity and complexity and decreasing automaticity of the central processes by which they are mediated. Extending Head's reasoning, one would expect that decision processes executed at different levels of this hierarchy differ systematically in the degree to which they demand activation.

Of the several available methods for measuring activation, perhaps the most sensitive and reliable is the measurement of sympathetic/parasympathetic activity as reflected in pupillary diameter (8). Pupillary dilations indicating momentary increases in CNS activation as a function of processing load (9) have been reported for short-term memory (10), problem-solving (11), and other complex information-processing tasks (12). Further, pupillometric measures have shown a striking correspondence to electrophysiological indices of activation in a long series of studies of cortico-reticular interactions (13). The pupillary dilations indicative of CNS arousal may be mediated by either increased forebrain inhibition of the Edinger-Westphal nuclei or increased sympathetic discharge (14). Thus pupillometric methods appear well-suited to the measurement of short-term activation changes in man that occur in information-processing tasks.

## EXPERIMENT I

### Method.

Sixteen undergraduates served as observers in the first experiment using a name criterion for judging 144 letter pairs that were presented tachistoscopically on a computer-controlled cathode ray tube display. Random dot patterns preceded and followed presentation of the letter pair so that the illumination level of the display was constant at all times. The display field subtended a visual angle of  $.5^\circ$  and was viewed at a distance of 4 m. Observers initiated each trial with a button press, which was followed one second later by the presentation of the letter pair for 100 msec. Two



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sec following stimulus onset, a response cue was displayed and the observer indicated his judgment by pressing one of two microswitches. Pupillary diameter was measured using a Whittaker 1053 TV pupillometer and was recorded at 20 msec intervals between trial initiation and response cue presentation. Room illumination was 17 footlamberts.

Six letters (AEIBRH) were employed and displayed in either upper or lower case. Of the 146 trials, 36 letter pairs were physically identical (PI), 36 were identical at the level of naming (NI) and 72 were of different (D) names.

Following the main experimental session, pupillometric measurements were taken in a series of 16 control trials, in which the stimuli were always the letter pair (XX) and the subject was instructed to press the "same" switch following the response cue. Thus encoding and decision processes were not required in the control series.

Pupillary and behavioral data from each trial were stored on disc for later analysis. Artifact detection was performed blindly with respect to stimulus type and response correctness by visual inspection of individual evoked pupillary responses. All trials containing major artifacts were discarded. Trials with small artifacts occurring in non-critical periods were corrected by linear interpolation. This procedure rejected approximately 5% of all trials in each of the stimulus categories (PI = 5.4%, NI = 4.7% and D = 4.6%).

### Results.

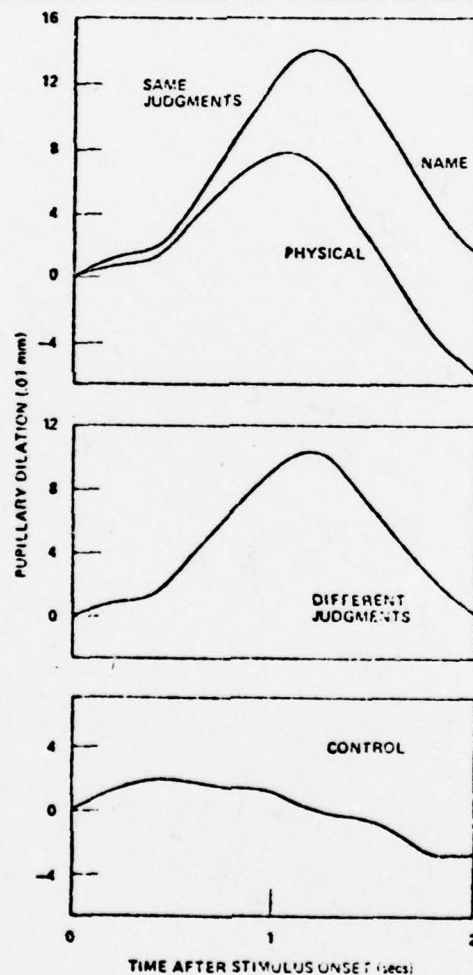
Under these conditions, subjects made few errors of judgment, but the percentage of errors differed significantly among the stimulus categories (PI = 1.4%, NI = 10.4% and D = 1.7%;  $F(2,30) = 14.09$ ,  $p < .001$ ). More errors occurred for letter pairs sharing the same name than for physically identical or different letter pairs.

Performance of the letter-classification task was associated with increased pupillary dilation. For each subject separate averaged evoked pupillary responses were computed for all artifact-free control and errorless experimental trials. The difference between prestimulus pupillary diameter and pupillary diameter averaged during the decision interval between stimulus presentation and response was significantly larger in experimental than in control trials ( $t(15) = 2.47$ ,  $p < .02$ ). Thus the pupillometric

measure appears sensitive to the encoding and decision components of the letter-classification task.

The degree of dilation observed in the decision interval for correct same judgments depended upon level of processing required to match the letters of the stimulus pair. Figure 1 presents the group averaged evoked pupillary responses for all experimental conditions. For the same judg-

FIGURE 1.



Average evoked pupillary responses for same, different and control judgments for a group of 16 subjects in a letter matching task using a name-level criterion.

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ments, these differences are most apparent in the second half of the decision interval. The mean dilation in the 1 sec period preceding the response cue differed significantly between the two levels of same judgments ( $t(15) = 2.68, p < .05$ ). The dilation observed for correct different judgments was of intermediate amplitude.

## EXPERIMENT II

A more stringent test of the relationship between processing level and task-induced activation may be obtained by employing a more elaborated hierarchical processing structure in the letter matching task. For this reason a second experiment was performed using a category-level criterion for judgment, in which the subject responds "same" if both letters are members of the same category, either vowels or consonants. In the second experiment 24 letter pairs were physically identical, 24 were identical at the level of naming, and 24 differed in name but were members of a common category (CI). Seventy-two letter-pairs differed in both name and category membership. Sixteen naive individuals served as subjects. In all other respects, the methods of the two experiments were identical.

### Results.

The results of this second experiment confirmed in more detail the relations between the level of hierarchical processing and task-induced activation. As in the first experiment, subjects made few errors of classification but the percent of judgment errors differed significantly among the experimental conditions (PI = 0.2%, NI = 2.9%, CI = 8.1% and D = 0.5%;  $F(3,45) = 4.24, p < .025$ ).

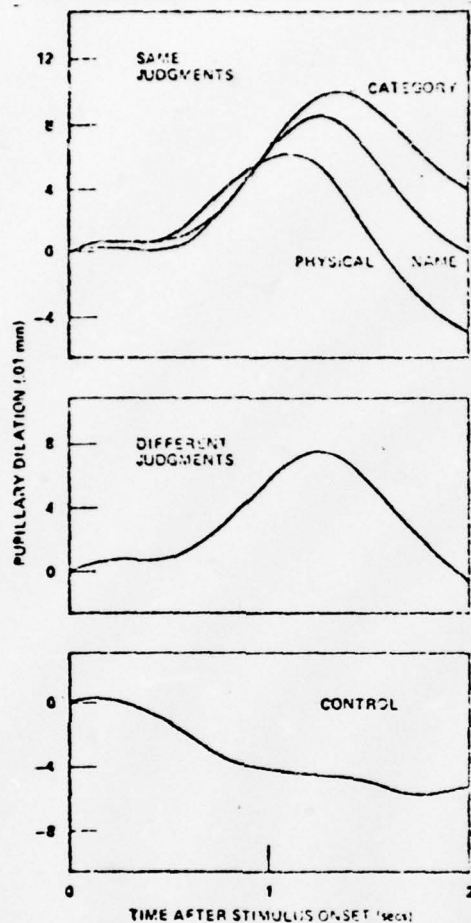
The averaged evoked pupillary responses for the second experiment are shown in Figure 2. As in the previous experiment, few trials were rejected for artifacts in the pupillometric data and these rejections were not selectively distributed across stimulus conditions (PI = 4.4%, NI = 4.6%, CI = 5.0% and D = 4.2%). And as before, pupillary dilation during the decision interval was significantly larger on experimental than on control trials ( $t(14) = 3.72, p < .01$ , the control trial data of one subject being lost in computer malfunction).

As might be apparent from Figure 2, highly reliable differences are present in the averaged evoked pupillary responses for correct same judgments as a function of the level to which the letter pair must be processed

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FIGURE 2.



Averaged evoked pupillary responses for same, different and control judgments for a group of 16 different subjects in a second experiment using a category-level criterion.

before reaching a correct decision of identity. For the three types of letter pairs that may be judged "same" by the category criterion, the averaged pupillary dilation in the 1-sec interval preceding response cue onset is smallest for physically identical letter pairs and largest for categorically identical pairs of different names. These differences in dilation amplitude are highly significant ( $F(2,30) = 6.46, p < .005$ ). Further the latency to peak pupillary response is significantly larger for letter pairs requiring higher levels of processing (PI = 1.145 sec, NI = 1.306 sec and CI = 1.345

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sec;  $F(2,30) = 6.73$ ,  $p < .005$ ). Thus less automatic processing of same letter pairs within this hierarchically organized cognitive system (7) appears to be associated with larger amounts of activation for greater periods of time.

## DISCUSSION

In both experiments, the amplitude of the averaged evoked pupillary response for correct different judgments was intermediate between those observed for the simplest and most complex same judgments. This result is in agreement with reaction-time data obtained with simultaneously presented letter pairs (7,15). One interpretation of both sets of findings is that some different letter pairs can be judged to be different on the basis of physical comparison, whereas others require full processing before a correct classification can be made. The apparent heterogeneity of the different judgments for simultaneously presented letter pairs therefore does not cloud the orderly relations observed between processing depth and task-induced activation observed for correct same judgments.

The use of the letter matching as a procedure for the investigation of analysis and decision processes carried out at different levels of a hierarchically organized cognitive system coupled with the use of pupillometric measurements to assess momentary shifts in centrally regulated autonomic activation provides a unique opportunity to test the Jacksonian hypothesis that more complex cognitive processes require a greater level of activation or "vigilance" for their successful execution. The data from both experiments lend support to this hypothesis. They suggest a pattern of nervous system organization in which the presumably forebrain mechanisms that specifically mediate complex cognitive processes exert reasonably direct, short-latency control of brainstem activation systems to provide the momentary level of central activation required. However reasonable such an interpretation might be, it is not without its difficulties. First, despite several decades of serious investigation, the mechanism by which brainstem activation systems affect the efficiency of cortical information processing remains puzzling (16). Second, the various signs taken as indicators of nervous system activation are not always in perfect agreement. Activation cannot therefore be a unitary variable and care must be exercised to specify exactly what measures of nervous system activity are taken as indicators of activation in any particular instance. Third, pupillometric measures, although classically associated with more central indicators of brain activation (13), are still peripheral autonomic signs and quite re-

moved from those central processes that one would wish to study directly. Nonetheless, the close relationship between peripheral patterns of pupillary dilation and the level of cognitive processing observed in the present experiments provide strong support of Jackson's idea that vigilance is a critical parameter of the higher information-processing functions of the human brain.

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#### REFERENCES

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1. J. Jackson, Lancet 3161, 555 (1884).
2. H. Head, Aphasia and Kindred Disorders of Speech (Macmillan, New York, 1926).
3. H. Magoun, The Waking Brain (Ch. Thomas, Springfield, Ill., 1958).
4. D. Wolgin, J. Cytawa, and P. Teitelbaum, in Hunger: Basic Mechanisms and Clinical Implications, D. Novin, W. Wyrwicka and G. Bray, Eds. (Raven, New York, 1976).
5. D. Kahneman, Attention and Effort (Prentice-Hall, Englewood Cliffs, N. J., 1973).
6. M. Posner and S. Boies, Psych. Rev. 76, 391 (1971).
7. M. Posner and R. Mitchell, Psych. Rev. 74, 392 (1967).
8. B. Goldwater, Psych. Bull. 77, 340 (1972); D. Kahneman, B. Tursky, D. Shapiro, and A. Crider, J. Exp. Psych. 79, 164 (1969).
9. D. Kahneman, J. Beatty, and I. Pollack, Science 157, 218 (1967).
10. D. Kahneman and J. Beatty, Science 154, 1583 (1966).
11. J. Bradshaw, Quart. J. Exp. Psych. 20, 116 (1968).
12. E. Hess and J. Polt, Science 143, 1190 (1964); A. Paivio, in The psychophysiology of Thinking, F. McGuigan and R. Schoonover, Eds. (Academic Press, New York, 1973).
13. G. Moruzzi, in Reviews of Physiology: Biochemistry and Experimental Pharmacology (Springer-Verlag, New York, 1972).
14. I. Loewenfeld, Documenta Ophthalmologica 12, 185 (1958).
15. M. Posner, S. Boies, W. Eichelman, and R. Taylor, J. Exp. Psych. 79, 1 (1969).
16. J. Schlag, in Handbook of Electroencephalography and Clinical Neurophysiology 2, O. Creutzfeldt, Ed. (Elsevier, Amsterdam, 1974).



ACTIVATION AND SIGNAL DETECTION: A PUPILLOMETRIC ANALYSIS

→ P.V.

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## ABSTRACT

Seven listeners performed an auditory signal detection task with a marked signal window and a rating-scale response procedure in which pupillary diameter was measured as an indicator of momentary visceronomic activation. Both basal pupillary diameter and pupillary dilation in a 500 msec warning interval were unrelated to performance parameters of the perceptual task. Pupillary dilations during the detection/decision interval were related to judgment category on signal ( $F(3,18) = 4.449, p < .025$ ) but not on non-signal trials ( $F(2,12) = 0.014$ ). Conditional analyses demonstrated that probability of correct response varies as a function of pupillary dilation in the detection/decision interval on signal trials but not on non-signal trials. These data suggest that the sensitivity or gain of pre-decisional auditory processes are activation-dependent.

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## INTRODUCTION

Information processing tasks differ in the extent and duration of the demands that they place upon the limited capacity of the human nervous system to handle information. For most tasks, processing demands are not constant, but vary from moment to moment in response to changes in the functional organization of the task. These demands may be thought to represent the cognitive workload associated with the task, a time-varying function of the demand for limited resources.

One approach to the problem of measuring momentary cognitive workload stems from observations indicating that momentary workload may be directly reflected in the momentary level of nervous system activation (Kahneman, 1973; Pribram & McGuiness, 1975). Of the various indicators of activation, pupillometric measurement techniques (Loewenfeld, 1958; Hess & Polt, 1964; Goldwater, 1972) appear to be most sensitive and reliable (Kahneman, Tursky, Shapiro & Crider, 1969).

The present study utilizes pupillary measurement to assess the role of activation in the regulation of a simple and relatively well-understood (Green & Swets, 1966) cognitive function, sensory signal detection. Signal detection differs from sensory discrimination in that a decision is required only as to the probability that a specifiable sensory signal has been presented against a background of statistically specified noise.

Although perceptual processes appear to proceed quite effortlessly and place little demand upon the limited capacity of the human information-

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processing system (Kahneman, 1973), small but reliable pupillary dilations accompany the detection of both visual and acoustic signals at near-threshold intensities. Hakerem and Sutton (1966) examined the pupillary movements that accompany the perception of weak visual stimuli and were able to show a dilation for signals that were detected which was absent for signals that were missed. More recently Beatty and Wagoner (Note 1) provided a pupillometric analysis of activation in the detection of weak acoustic signals using a rating-scale response procedure (see Green & Swets, 1966). Using unmarked observation intervals, no pupillary dilations were observed in the absence of a signal regardless of the outcome of the observer's decision. In the presence of a signal, a dilation of the pupil appeared in the interval between signal delivery and response cue onset. The magnitude of this dilation varied monotonically with the observer's rated probability that a signal had been presented.

One difficulty with both these experiments is that the subject did not know the exact moment at which a signal might appear. Thus whereas pupillary dilations following signal onset might accurately reflect activation accompanying perceptual and decision processes, on nonsignal trials there is no clear marker upon which perceptual and decision processes might be synchronized. This problem may be remedied by providing the subject with a warning stimulus to indicate the onset of a trial and signal onset stimulus to provide exact temporal information concerning the onset of the signal if a signal is presented. In these ways the time course of perception and decision is controlled exactly for both signal and non-signal trials.

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## METHOD

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### Subjects.

Seven university students served as subjects to partially fulfill the requirements of an introductory psychology course.

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### Psychophysical task.

Subjects were required to detect weak acoustic signals in a background of acoustic noise. Signals were 100 msec 1 kHz sinusoidal segments (Hewlett-Packard 200B Audio Oscillator). Acoustic noise was obtained from a Hewlett-Packard 8057A Precision Noise Generator and band-limited (.1-2.6 kHz) by a Krohn-Hite 330M band-pass filter. Signal and noise were mixed in an operational amplifier manifold with computer-con-



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trolled switching (Hewlett-Packard 2116B computer). The composite waveform was amplified (McIntosh 75 power amplifier) and presented to the listener with calibrated binaural earphones (Koss Pro SLC). Signal intensity was adjusted individually for each subject to obtain a performance level of approximately  $P(\bar{A}) = .85$  (see data analysis for explanation of  $P(\bar{A})$  ).

Trial onset and signal window onset were indicated to the listener by a pair of fixation lights, two light-emitting diodes separated vertically by 1 cm at a distance of 2 m. The two fixation lights were never illuminated simultaneously, keeping illumination constant in the subject's visual field. Trials were initiated 1-2 sec after the subject fixated the diode display. Trial onset was indicated by switching the upper diode on and the lower diode off. This warning signal lasted 500 msec, following which the pattern of illumination was reversed and a 100 msec sinusoidal burst was added to the band limited noise with a probability of .5. The trial was terminated 1.5 sec following stimulus window onset by the response cue, a 100 msec break in the background noise. The listener then indicated his decision as to the probability that a signal was presented on that trial by depressing one of four microswitches (1--yes/certain, 2--yes/uncertain, 3--no/uncertain or 4--no/certain) following the rating scale procedure of Green and Swets (1966). Following each decision, feedback was provided to the listener by a 500 msec period of sinusoid without noise if a signal had been presented and a 500 msec period of silence otherwise. The experimental session consisted of three blocks of 64 trials each.

#### Pupillometric measurement.

Pupillary diameter was measured continuously for 2.5 secs, from 500 msec preceding the onset of the warning signal to the onset of the response cue. Measurements were made with a Whittaker 1000 TV pupillometer. This instrument does not obstruct the subject's field of view, permitting normal fixation of the diode display. The pupillometer computes the vertical pupillary diameter from an infrared video image of the eye. This image together with an indication of the computed diameter is continuously available to the experimenter to assure that the data obtained are free of artifacts. Pupillary diameter was sampled by the computer at 20 msec intervals throughout the trial. At the end of each trial, the pupillary data were displayed graphically to the experimenter as a time series. Any trial containing an eyeblink was discarded. Data from accepted trials were stored individually on disc for later analysis.

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### Data analysis.

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#### Psychophysical data.

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Listener sensitivity was determined using non-parametric methods of signal detection theory. A receiver-operating characteristic (ROC) was computed for each listener and the area beneath that function was calculated. This proportion,  $P(\bar{A})$ , is a non-parametric bias-free estimator of sensitivity that varies between .5 when no information is transmitted by the listener to 1.0 when the listener performs without error.  $P(\bar{A})$  also corresponds to the probability of correct response when a two-alternative forced-choice procedure is employed (Green & Swets, 1966).

#### Pupillometric data.

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Averaged evoked pupillary responses were computed for each subject by stimulus condition (signal or nonsignal) and response category (1 through 4), with one exception. Averaged pupillary responses were not computed for high-confidence false alarms (yes/certain judgments in the absence of a signal), as these did not occur in sufficient number to permit the computation of stable averages. Thus seven averaged pupillary responses constituted the basic pupillometric data for each subject. From these responses, the following measurements were calculated: baseline or mean pupillary diameter preceding the warning signal, mean pupillary dilation during the warning signal relative to pupillary diameter at its onset, and mean pupillary dilation during the detection/decision period between signal window onset and response cue relative to pupillary diameter at signal window onset.

### RESULTS

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#### Primary psychophysical results.

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Individual ROC curves for each of the seven listeners are plotted in Figure 1.  $P(\bar{A})$  ranged between .81 and .87.

#### Primary pupillometric results.

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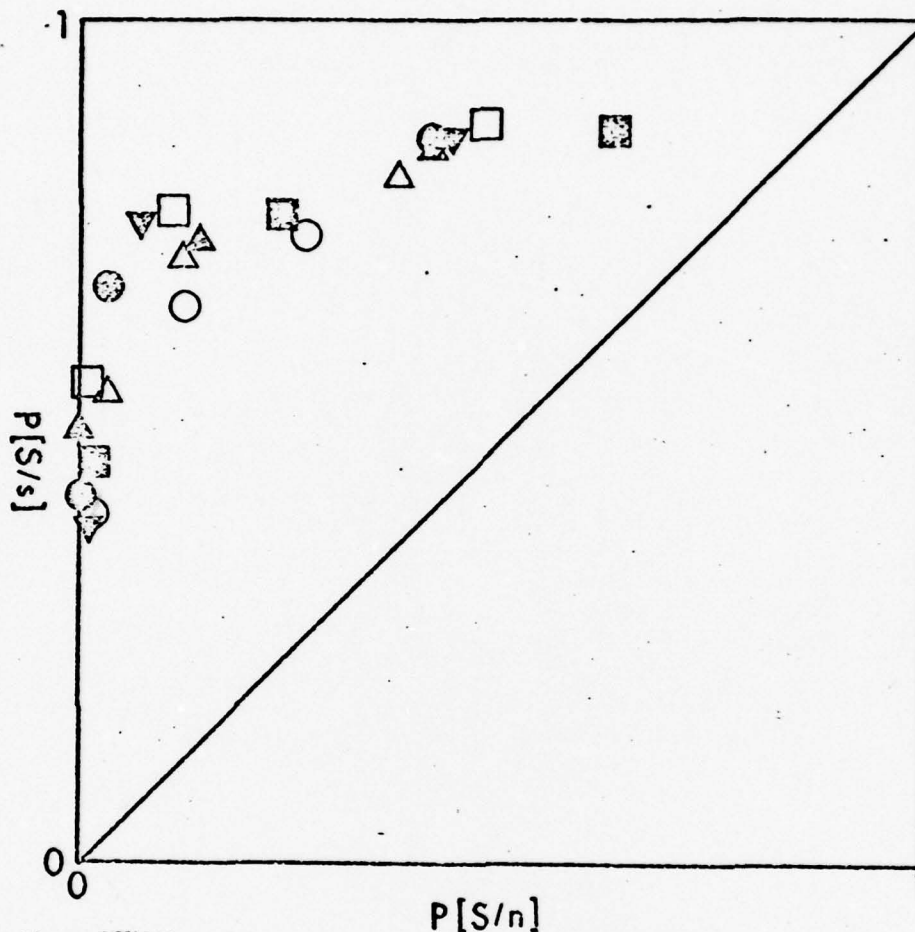
Baseline pupillary diameter in the interval preceding the warning signal was not related to response outcome on either signal ( $F(3,18) = .941$ , N. S.) or nonsignal ( $F(2,12) = 1.163$ , N. S.) trials.

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**FIGURE 1**

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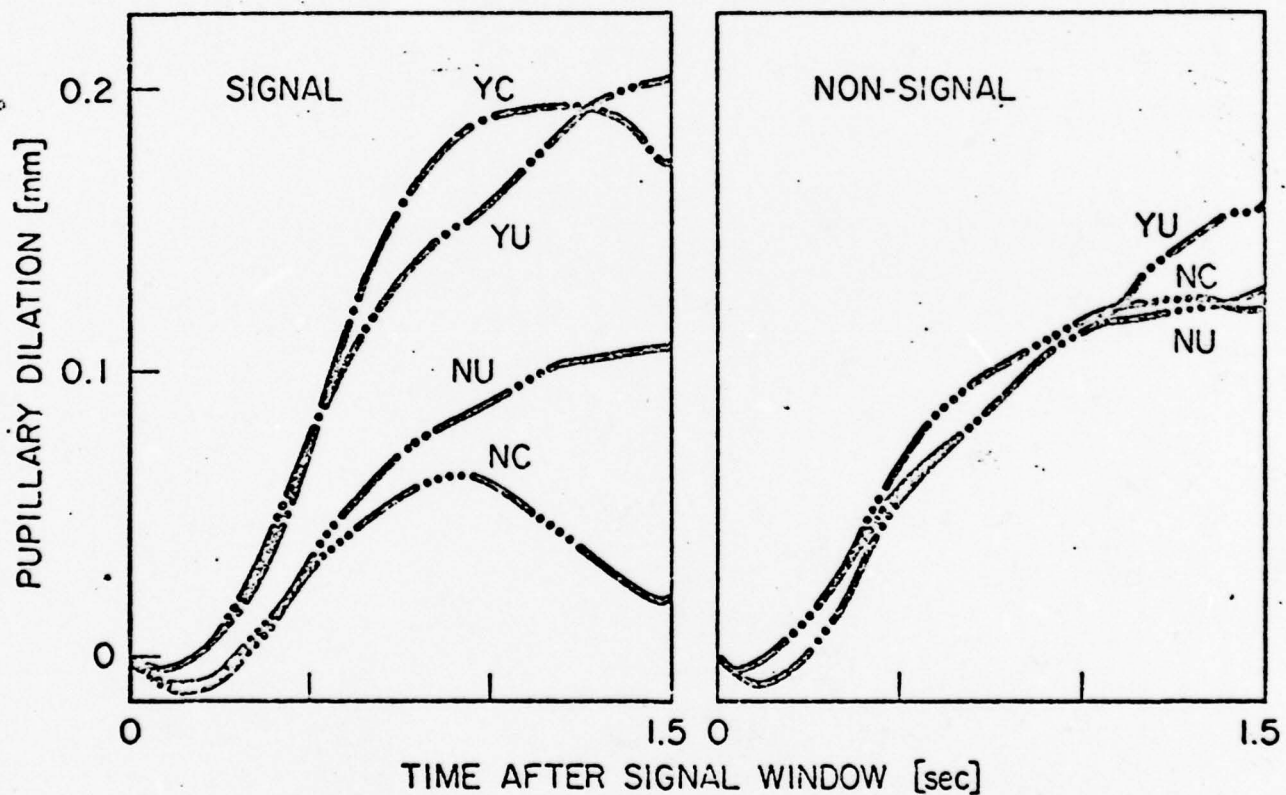
Receiver operating characteristics (ROC) for each of the seven listeners in the experiment.  $P(\bar{A})$  is a measure of the proportion of the plotting space contained beneath the ROC curve for each subject, and provides an estimate of listener sensitivity.  $P(S/s)$  is the conditional probability of deciding a signal was presented given that a signal was actually present.  $P(S/n)$  is the conditional probability of making the same decision in the absence of a signal. Different symbols represent different listeners. For each listener, three criteria are plotted from the rating scale response data.

Similarly, no significant differences in pupillary dilation during the 500 msec warning interval were present in these data. (Signal trials:  $F(3,18) = .951$ , N. S.; Nonsignal trials:  $F(2,12) = .609$ , N. S.).



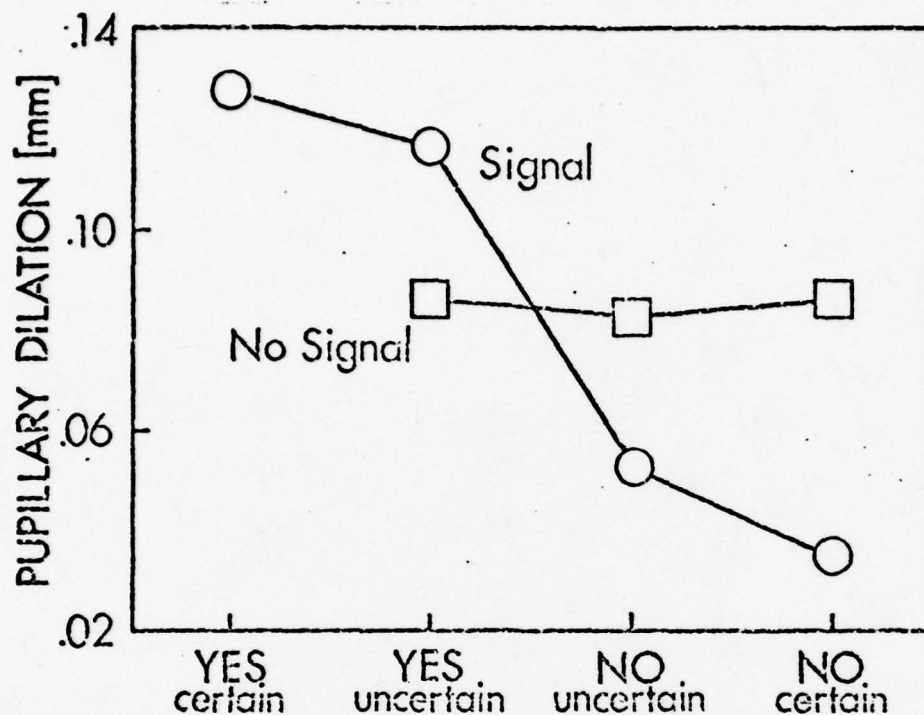
Pupillary dilations in the 1.5 sec detection/decision period were related to decision outcome in the presence of a signal. Figure 2 presents the averaged evoked pupillary responses from the onset of the signal window to the onset of the response cue. Figure 3 shows the mean pupillary dilations in this period as a function of stimulus and response category. Statistical analyses of these data reveal two separate functions relating pupillary dilation and decision outcome. On nonsignal trials, a constant dilation is observed in the three obtained response categories (yes/uncertain,

FIGURE 2



Averaged evoked pupillary responses, for the 1.5 sec interval between the offset of the warning light and the onset of the response cue. The left graph presents responses for signal trials for each of the four response classes. The right graph presents data for non-signal trials.

FIGURE 3



Mean pupillary dilation in the 1.5 sec decision interval between warning offset and response cue onset, for signal and non-signal trials separately by subject response.

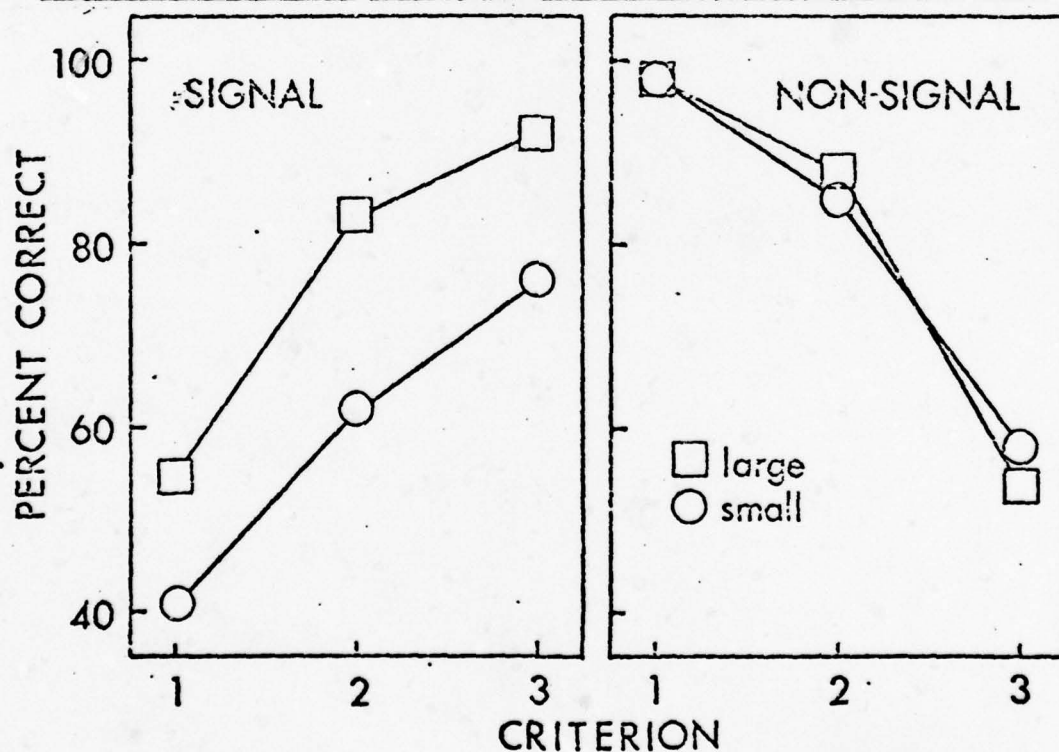
no/uncertain and no/certain). The averaged dilations in these categories do not differ significantly from each other ( $F(2,12) = .014$ , N.S.). On signal trials, however, pupillary dilation in the detection/decision period varies directly with response category in a systematic manner ( $F(3,18) = 4.449$ ,  $p < .025$ ).

#### Dilation-contingent psychophysical results.

That pupillary dilation in the detection/decision period varies as a function of response category only in the presence of a signal suggests that variations in activation as indexed by pupillary movements in this period primarily affect input processing functions. This argument implies that a sensitivity measure such as  $P(\bar{A})$  should be greater on trials with large di-

lations than on those with small dilations in the detection/decision period. To test this hypothesis,  $P(\bar{A})$  was computed separately for dilations above and below the mean dilation for each subject. For small dilation trials, the average value of  $P(\bar{A})$  was .78; for large dilation trials it was .89. These means differ significantly from each other ( $t(6) = 2.46$ ;  $p < .05$ ). The differential sensitivity on large and small dilation trials is not a function of performance on nonsignal trials, where the average percents correct for simple yes-no judgments were 88 and 86, respectively ( $t(6) = .59$ , N.S.). Rather it is the performance on the signal trials that affects  $P(\bar{A})$ . For large dilation trials, the percent correct detection is 83 as compared with 62 for small dilation trials ( $t(6) = 3.23$ ,  $p < .01$ ). The full conditioned percent-correct functions are shown in Figure 4.

FIGURE 4



Percent correct as a function of criterion and trial type separately for large and small dilations in the detection/decision period. Pupillary diameter affects decision accuracy only in the presence of a signal.



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## DISCUSSION

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These data have several implications concerning the relationship between brain activation, as indicated by viscerosomatic measures, and perceptual events. First, the absence of any relation between pretrial pupillary diameter and judgment quality suggests that pretrial alertness does not predict decision accuracy in well-rested subjects tested in short, clearly marked trials. A similar independence of basal pupillary diameter and event-related pupillary dilations has been reported by Kahneman and Beatty (1967). However if a detection experiment were extended to approximate a vigilance-type task, pupillary diameter at trial onset might be expected to reflect tonic activation changes (Yoss, Moyer, & Hollenhorst, 1970; Yoss, Moyer, & Ogle, 1969) and thereby be related to performance efficiency.

Second, the absence of any relation between dilation during the warning interval and decision outcome suggests either that preparation during this period was homogeneous across trials or that preparatory effects are not mediated by activation changes.

Third, the finding that dilations during the detection/decision interval are systematically related to decision outcome only on trials in which a signal was actually presented indicates that it is the predecisional perceptual processes that are activation dependent. This would be the case if the sensitivity of the system of sensory analyzers was regulated by momentary shifts in activation. This interpretation is supported by the conditional detectability analysis, in which performance is compared on trials with large and small dilations. Sensitivity, as indexed by  $P(\bar{A})$ , is significantly greater on large dilation trials. Moreover, the magnitude of the difference is large. The fact that this difference in sensitivity is mediated solely by listener performance on signal trials suggests that the effect of activation is to shift the mean position of the signal + noise distribution with respect both to the position of the noise-alone distribution and to the set of decision criteria, which apparently remain fixed across trials (Green & Swets, 1966). Thus the gain of the auditory system appears to be activation-dependent, whereas the subsequent perceptual decision processes are activation dependent, within the boundaries of the present experiment.

Why changes in perceptual sensitivity should affect performance on signal trials but not on non-signal trials may be explained directly with the signal detection model. The usual signal-detection formulation (Green & Swets, 1966) proposes that in the absence of a signal, the input to the deci-

sion process is not fixed, but may be represented as a normally-distributed random variable. The presentation of a signal results in a new distribution with an expected value equal to the mean of the nonsignal distribution plus some quantity that increases monotonically with signal detectability. Changing the gain of the predecisional perceptual system must affect the position of the signal distribution more than the noise distribution by a factor that is proportional to the detectability of the signal employed. In the present experiment, the signal was quite highly detectable ( $P(\bar{A})$  was approximately .85). Under these conditions, shifts in sensitivity will affect performance on signal trials much more than on noise trials. As the intensity of the signal is decreased, however, this asymmetry of effect will be reduced.

Fourth, the striking regularity of these pupillary movements deserves emphasis. Although the magnitude of the dilations in the detection/decision period is quite small, they are nonetheless reliable indicators of ongoing cognitive processing. For example, in another experiment using unmarked observation intervals, we were able to predict whether or not an individual signal would be detected with accuracies between 66 and 93 percent from an analysis of single-trial pupillary movements (Beatty, Note 2). In the present experiment, partitioning the behavioral data as a function of dilation magnitude resulted in statistically significant, large-magnitude changes in hit rate. The fine movements of the iris musculature apparently reflect with considerable accuracy momentary shifts in viscerosomatic activation that are systematically related to cognitive processing.

Finally, the argument has been made (see Goldwater, 1972, for a review) that the pupillary dilations observed in information-processing experiments reflect emotional arousal or anxiety about task performance and not processes intrinsic to the performance of the task itself. Such arguments are based upon the observation that larger pupillary dilations occur as the difficulty of the processing task increases and upon the assumption that more difficult tasks induce greater performance anxiety. This interpretation seems unlikely for the present experiment. Performance anxiety should vary as a function of decision certainty in a decision task, with more performance anxiety characterizing uncertain than certain judgments. Yet in our data, decision certainty is without effect on pupillary dilation on nonsignal trials. On signal trials, the largest and the smallest dilations are associated with certain decisions, with dilations for uncertain decisions being of intermediate amplitudes. Pupillary dilations during the detection/decision interval of an acoustic signal detection task appear not to be related to performance anxiety, but instead to factors that are intrinsic to per-

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ceptual processing.

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#### REFERENCE NOTES

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1. Beatty, J., & Wagoner, B. L. Pupillary measurement of sensory and decision processes in an acoustic signal-detection task. Paper presented at the meeting of the Psychonomic Society, Denver, Colorado, 1975.
2. Beatty, J. Prediction of detection of weak acoustic signals from patterns of pupillary activity preceding behavioral response. UCLA Technical Report, 27 May 1975.

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#### REFERENCES

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- Goldwater, B. C. Psychological significance of pupillary movements. Psychological Bulletin, 1972, 77, 340-355.
- Green, D. M., & Swets, J. A. Signal detection theory and psychophysics. New York: Wiley, 1966.
- Hakerem, G., & Sutton, S. Pupillary response at visual threshold. Nature, 1966, 212, 485.
- Hess, E. H., & Polt, J. H. Pupil size in relation to mental activity during simple problem solving. Science, 1964, 143, 1190-1192.
- Kahneman, D. Attention and effort. Englewood Cliffs, New Jersey: Prentice-Hall, 1973.
- Kahneman, D., & Beatty, J. Pupillary responses in a pitch discrimination task. Perception and Psychophysics, 1967, 2, 101-105.
- Kahneman, D., Tursky, B., Shapiro, D., & Crider, A. Pupillary, heart rate and skin resistance changes during a mental task. Journal of Experimental Psychology, 1969, 79, 164-167.
- Loewenfeld, I. E. Mechanisms of reflex dilations of the pupil, historical and experimental analysis. Documenta Ophthalmologica, 1958, 12, 185-448.
- Pribram, K. H., & McGuiness, D. Arousal, activation, and effort in the control of attention. Psychological Review, 1975, 82, 116-149.
- Yoss, R. E., Moyer, N. J., & Hollenhorst, R. W. Pupil size and spontaneous pupillary waves associated with alertness, drowsiness, and sleep. Neurology, 1970, 201, 545-554.
- Yoss, R. E., Moyer, N. J., & Ogle, K. N. The pupillogram and narcolepsy. Neurology, 1969, 19, 921-928.



→ and ACTIVATION AND SUSTAINED ATTENTION:

A PUPILLOMETRIC STUDY OF AN AUDITORY VIGILANCE TASK

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## INTRODUCTION

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The study of sustained attention in man is virtually defined by an experimental paradigm, the vigilance task (Jerison, 1977) in which an observer is required to monitor a single display for prolonged periods to detect infrequent targets against a background of frequent nontarget signals. Under such conditions, performance normally deteriorates as a function of time on task, an effect that has been termed the "vigilance decrement." This decrement is usually attributed to a gradual decline in the level of central nervous system activation (Mackworth, 1969; Stroh, 1971; Mackie, 1977). Support for the activation theory of sustained attention comes primarily from experiments demonstrating that degraded performance in a vigilance task is associated with physiological signs of decreased activation.

Electroencephalographic (EEG) indicators of central nervous system activation have been investigated in vigilance tasks by several groups. Haider, Spong and Lindsley (1964), for example, were able to demonstrate that the amplitude of cortical event-related potentials (ERPs) declined with detection efficiency as a function of time on task. Further, ERPs to undetected targets were smaller than ERPs to detected targets, suggesting that detection failure is associated with activation-related lapses of sustained attention. Studies of changes in the spontaneous EEG rhythms in vigilance tasks also lend support to an activation theory of sustained attention. In particular, the presence of theta frequency (3 to 7 Hz) activity in the posterior EEG, an electroencephalographic sign of drowsiness (Rechtschaffen & Kales, 1968), often increases as performance deteriorates in vigilance-type tasks. Such effects have been reported by Oswald (1962), Williams et al. (1962), Groll (1966), and O'Hanlon and Beatty (1977). Beatty, Greenberg, Deibler, and O'Hanlon (1974) were also able to demonstrate that when operant conditioning procedures are employed to control posterior theta frequency activity during a vigilance task, operant suppression of theta activity abolishes the vigilance decrement whereas operant augmentation of theta activity increases the magnitude of the decrement, providing an experimental test of one aspect of the activation theory of sustained attention.

The major difficulty with the activation theory of sustained attention, as it is presently formulated, is that it falsely simplifies the complex nature of brain activation processes. For example, the original concept of the brainstem reticular formation as an undifferentiated, diffuse network that regulated the level of brain activation is no longer tenable. The anatomy of the brainstem activating systems is now known to be highly complex and intricately organized (Schlag, 1974). Physiologically, the effects of activation are also more complicated than was initially realized (Duffy, 1972). Similar

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complexities have appeared in studying the neurophysiological basis of sustained attention. Not all physiological indicators of activation appear to decrement in the vigilance task (Jerison, 1977); only indicators of activation appear to be related to sustained attention. Therefore, by analyzing the pattern of physiological activation that affects performance in the vigilance task, the physiological basis of sustained attention might be identified. The activation theory of sustained attention must then be modified to do justice to the complexity of the neuropsychological data.

One approach to this question may come from the analysis of different classes of physiological indicators of central nervous system activation, such as the movements of the pupils of the eye. The study of pupillary movements played a major role in the initial analysis of reticular activating system (Moruzzi, 1972). Recent technical advances have made pupillometric analysis a feasible approach to the study of brain activation and behavior in man.

#### Pupillary Signs of Brain Activation.

Pupillary diameter is determined by the relative excitation of the two muscle systems of the iris, the radially-oriented sympathetically-innervated dilator pupillae and the parasympathetically innervated sphincter pupillae. Thus, pupillary dilations result from either sympathetic activation or parasympathetic inhibition alone, or both factors in combination (Loewenfeld, 1958).

It is useful to distinguish two types of pupillary movements which differ in their temporal properties: the very short latency and short duration phasic responses and the much slower tonic pupillary movements, the durations of which may be measured in minutes or hours. In a wide variety of cognitive tasks, phasic pupillary responses appear to be closely related to momentary changes in information processing load (Goldwater, 1972). For example, phasic pupillary dilations are observed as items are stored in memory for immediate recall, the magnitude of the dilation being a nearly linear function of the number of items stored (Kahneman & Beatty, 1966). Similarly, in a perceptual discrimination task, the amplitude of the phasic pupillary response is a direct function of discrimination difficulty. These transient, processing-related dilations appear to be independent of tonic or baseline pupillary shifts (Kahneman & Beatty, 1967).

Changes in tonic pupillary diameter have been related to changes in alertness and fatigue. Yoss, Moyer and Hollenhorst (1970), in a study of narcoleptic patients, report that tonic pupillary diameter decreases by 50



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percent between full wakefulness and the onset of sleep. Further, a rapid dilation of similar magnitude is observed when the sleeping patient is awakened. This dilation is then maintained if the patient remains alerted.

Fatigue may also be reflected in tonic pupillary diameter. Peavler (1974) reports an attempt to assess the fatiguing effects of two different working procedures in a group of telephone operators. Pupillary diameter was measured at the beginning and at the end of an 8-hour work period using both working procedures. A larger and statistically more reliable decrease in pupillary diameter was observed in the operators when using the subjectively more fatiguing procedure. Lowenstein and Loewenfeld (1952) had previously reported a decrease of 1 to 1.5 mm in pupillary diameter over an 8-hour work period which they considered to be an autonomic sign of central nervous system fatigue.

Finally, tonic pupillary diameter has served as an indicator of physiological arousal in a series of acute animal experiments investigating the organization of brainstem activating systems, with full pupillary dilation indicating high physiological arousal (Moruzzi, 1972).

Thus, pupillary movements may reflect two aspects of brain activation. Phasic responses appear to be closely related to the demand imposed by ongoing cognitive processes, whereas tonic changes appear to reflect more global shifts in organismic activation. Since previous work has indicated that these two components of activation may be somewhat independent of each other (Kahneman & Beatty, 1967), the study of pupillary responses might be useful in clarifying the nature of the activation processes that appear to underlie sustained attention. To obtain such data, the following experiment was performed.

## METHOD

### Subjects.

Eleven persons served as subjects; three were members of the laboratory and eight were university students who were paid \$2.30/hr for their services. Three of the subjects were males.

### Experimental Environment.

Each subject was tested individually in a sound-attenuated experimental chamber. Acoustic white noise was presented over a loud speaker in the

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chamber to further mask extraneous noise originating in adjoining rooms.

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#### Stimuli.

A string of 1 kHz 50 msec tone bursts were presented every 3.2 sec. Tone bursts were generated by a Hewlett-Packard 200AB audio oscillator, electronically switched, amplified, and presented to the subject over binaural earphones. Target tones were attenuated by -3.5 db.

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#### Task.

Each subject was required to monitor the auditory display and report any targets detected by depressing a microswitch. The test was 48 minutes in duration, divided for purposes of analysis into nine segments of 5 minutes 20 seconds, each containing 12 target and 88 non-target stimuli. Subjects were given practice exposure to both kinds of stimuli before testing.

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#### Experimental Control.

The entire experiment was controlled by a general purpose laboratory computer (Hewlett-Packard 2116B), including stimulus presentation, data acquisition, data editing and data analysis.

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#### Pupillometric Measurement.

Pupillary diameter was measured on-line in the experiment using a Whittaker 1050S TV pupillometer. This device processes the image obtained from an infrared video camera, identifies the pupil using a specialized pattern-recognition algorithm, and computes the diameter of the image of the pupil. Pupillary diameter is transmitted to the computer as an analog signal and the processed image of the eye with an indication of the machine-identified pupil is displayed to the experimenter to assure that the pupillometer is providing accurate measurements; the experimenter could reject on-line pupillometric data that was inaccurately measured.

To obtain accurate pupillometric measurements over a prolonged period without interruptions the following procedures was employed. The subject sat in a comfortable upright chair and rested both chin and forehead on a Bausch and Lomb head rest. The video camera was positioned 15 cm from the subject's left eye and angled 35° to prevent interference with the sub-

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ject's field of view. A television monitor displaying the image of the eye at very low contrast was positioned 1 m from the subject in the center of the visual field to enable him to maintain a stable position in the pupillometer for the duration of the task.

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#### Data Acquisition.

Pupillometric data was sampled at 50 msec intervals and stored as time-series data on disc for later analysis. For analysis purposes, data was stored in 6.2 sec trials, with stimuli presented at 0 and 3.2 sec in each trial. No data was taken between 6.2 and 6.4 sec, during which time the control program performed other functions. Thus the data from each of the 9 segments of the experiment was stored as 50 6.2 sec trials. The 12 targets of each segment were always presented as the second stimulus of each trial. The knowledge that signals would appear on only even numbered signals was of little use to the 3 subjects who were acquainted with the experimental procedures, and was unnoticed by the 8 paid subjects. This permitted the differential analysis of the pupillary response to the non-target stimulus preceding detected and undetected target stimuli. Behavioral data on detection responses was also stored on disc for later analysis.

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#### Data Editing.

The digitized pupillary record of each trial was individually examined on a cathode-ray tube display after the experimental session. Trials were either accepted if no artifacts were present, edited if flawed by minor artifacts or rejected if contaminated by major artifacts. Editing was accomplished using a linear interpretation algorithm between uncontaminated data points on either side of the eyeblink or pupillometer artifact. If the artifact was in a critical region of the trial, during or immediately following presentation of either of the two stimuli, or was greater than about 500 msec in duration, the trial was rejected. Editing of the pupillometric data was blind with respect to both stimulus and response conditions. Across all subjects, 19 percent of all trials were rejected. The probability of trial rejection increased as a function of time in task, rising from 12 percent in the first third of the experiment, to 20 percent in the second and 25 percent in the final third. This increase in rejection rate is highly significant, as indicated by an analysis of variance ( $F(2, 20) = 7.270, p < .005$ ). However, there is no evidence to indicate that target and nontarget trials were differently affected.



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## Data Analysis.

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### Pupillometry.

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After editing, the averaged pupillary response was computed in each of the nine segments of the test for nontarget trials, trials with missed targets and trials with correctly detected targets. From these primary averages, six secondary averages were computed for each subject. The averaged pupillary responses to non-target stimuli by thirds of the test (segments 1, 2 and 3; 4, 5 and 6; 7, 8 and 9) were computed to test for the effects of time on task upon pupillometric measures. To test for the relations between pupillometric measures and performance, pupillary responses were averaged over all segments containing at least one hit, miss and nonsignal trial separately for each stimulus/response category. Tonic and phasic measures of pupillary activity were then computed from these averaged pupillary responses. Tonic pupillary diameter was estimated as the value of the pupillometric record at the onset of the second stimulus. Phasic pupillary response was computed as the maximal pupillary dilation in the 1.5 sec interval following presentation of the second stimulus. An analogous phasic pupillary measure was computed for the first stimulus in an analysis of differential responsiveness preceding detected and undetected targets.

### Performance.

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The performance of each subject was characterized by the percent correct detections in each segment of the experiment. These values were then averaged to obtain percent correct detections scores for each third of the vigilance test. False alarms, although infrequent (16 percent of all responses) were similarly analyzed.

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## RESULTS

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### Performance.

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The probability of correctly detecting a target declines systematically over thirds of the vigilance test, dropping from 83 percent in the first period to 73 percent in the middle period and to 69 percent in the final period of the task (see Figure 1). This performance decrement is highly systematic and reliable, as indicated by analysis of variance (ANOVA) ( $F(2, 20) = 9.403$ ,  $p < .005$ ). The degree of performance decrement was also analyzed by computing the slope of the linear function relating percent correct detection and period of the task. By this analysis eight subjects showed performance decrements and three did not.

FIGURE 1

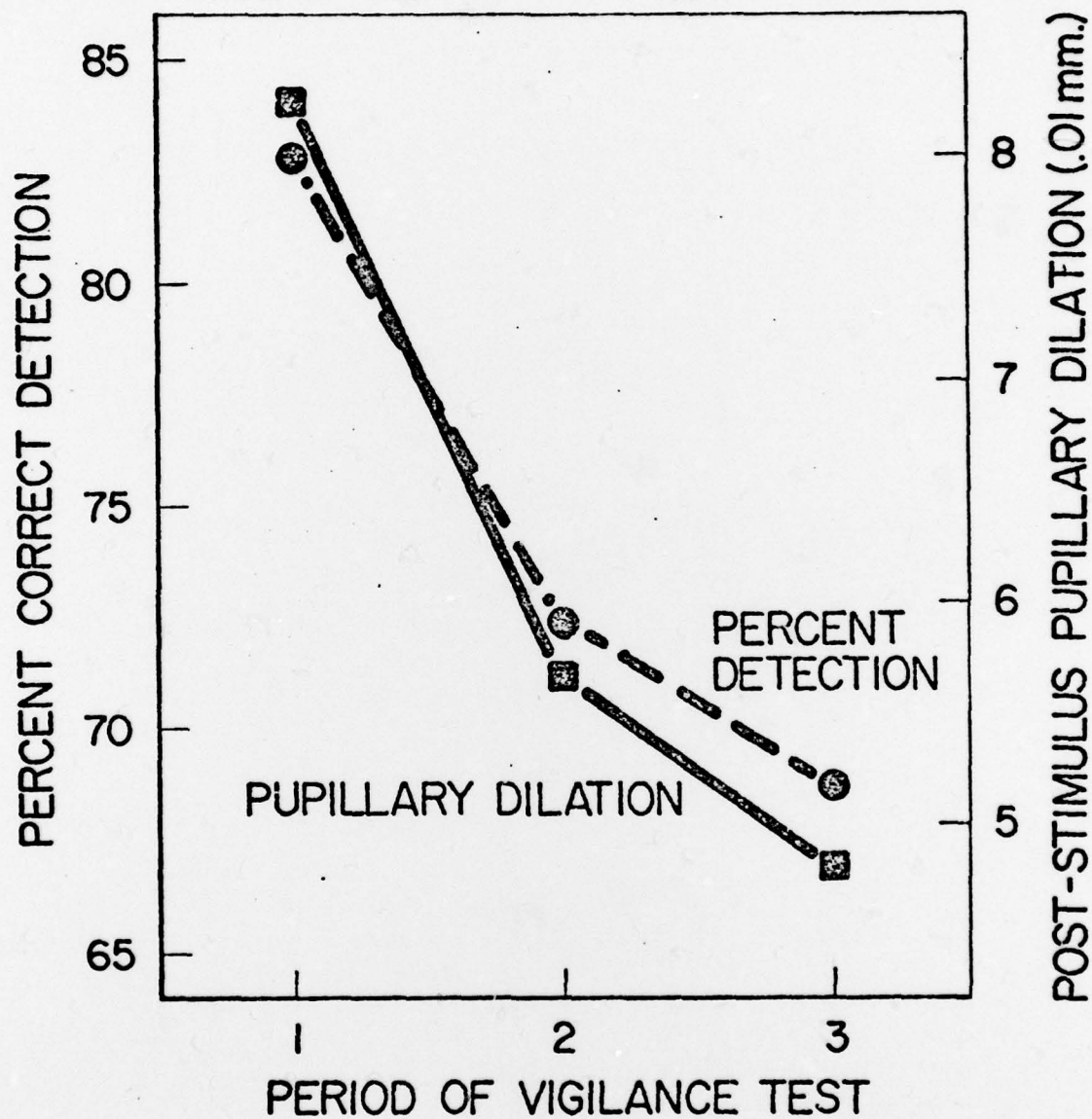


Figure 1. Percent targets correctly detected (circles) and mean pupillary dilation to nontarget stimuli (squares) averaged over eleven subjects as a function of period of task. Both measures change in a similar manner during the vigilance task.

Whether this performance decrement reflects a loss of sensitivity or a shift in response bias (Green & Swets, 1966) is not clear, as false alarms also decreased as a function of time on task. Although these rates were quite low (.03, .02, and .01 percent in the three periods of the experiment), the decline was highly significant ( $F(2, 20) = 9.721, p < .005$ ).

#### Pupillometry.

Tonic pupillary diameter (estimated as pupillary diameter at the onset of the second stimulus in a trial) did not vary significantly over periods of the task, as tested by analysis of variance ( $F(2, 20) = .048, N.S.$ ). Nor did any of several other estimators of tonic pupillary level yield a significant effect.

However, the amplitude of phasic pupillary dilations in response to task-relevant stimuli did decline systematically as a function of time on task, in a manner that closely paralleled the decrement in performance (see Figure 1). The maximum pupillary dilation in the 1.5 sec period following the onset of the nontarget stimulus declined significantly over thirds of the task, as tested by analysis of variance ( $F(2, 20) = 5.235, p < .01$ ). Figure 2 presents the evoked pupillary response waveforms for nontarget stimuli for the three periods of the task.

For target trials, the phasic pupillary response to target stimuli differed significantly for detected and undetected targets by t-test ( $t(10) = 4.000, p < .01$ ). Figure 3 presents the evoked pupillary response waveforms for both detected and undetected targets over all periods of the task. The phasic pupillary response for detected targets is more than twice as large as the response to undetected targets. However, detected and undetected targets do not differ significantly in baseline pupillary diameter at stimulus onset ( $t(10) = .152, N.S.$ ).

An attempt was also made to predict detection of target stimuli by analysis of the pupillary response to the immediately preceding non-target stimulus. However, neither phasic dilation nor tonic baseline differed significantly between nontarget stimuli preceding detected and undetected targets.

To assess the strength of the relationship between phasic pupillary activity and performance, a correlation was computed for each subject between percent targets detected in each 5 minute 20 sec block and the amplitude of the dilation to nontarget stimuli in that block over the nine blocks of the experiment. For the three subjects who did not show a performance decrement



FIGURE 2

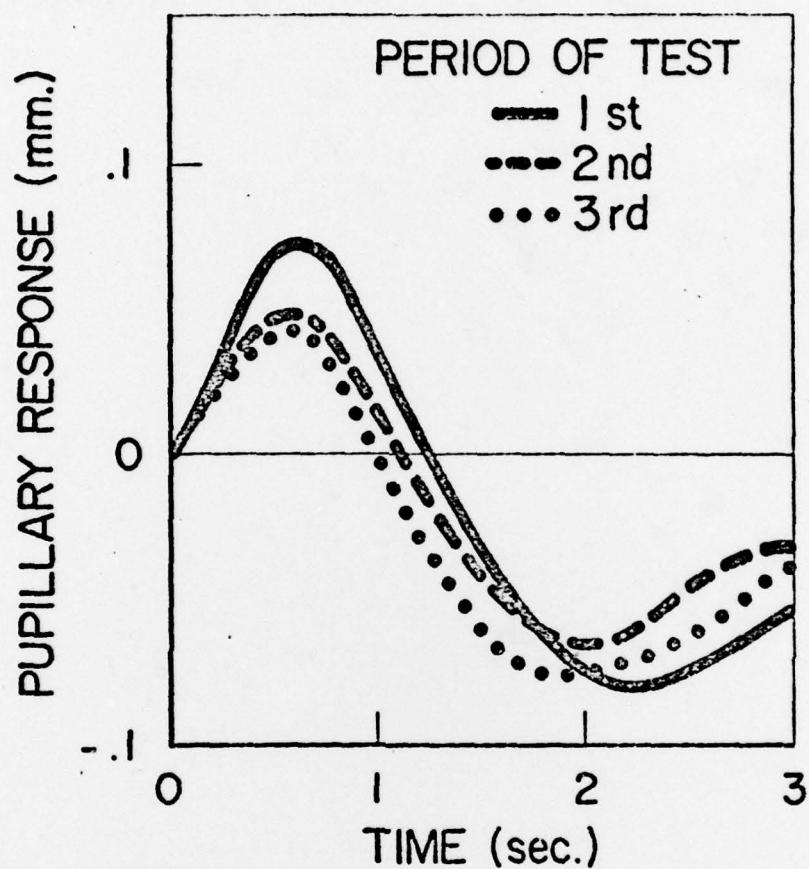


Figure 2. Averaged evoked pupillary responses to non-target stimuli for the first, second and third period of the vigilance task. Differences in peak dilations are highly significant.

over time in the task, the mean correlation between dilation and performance was  $+0.01$  (range:  $-0.19$  to  $+0.24$ ). For the eight subjects in which performance deteriorated over time all correlations were positive. The mean value of the correlation was  $.41$  (range:  $+0.14$  to  $+0.77$ ).

FIGURE 3.

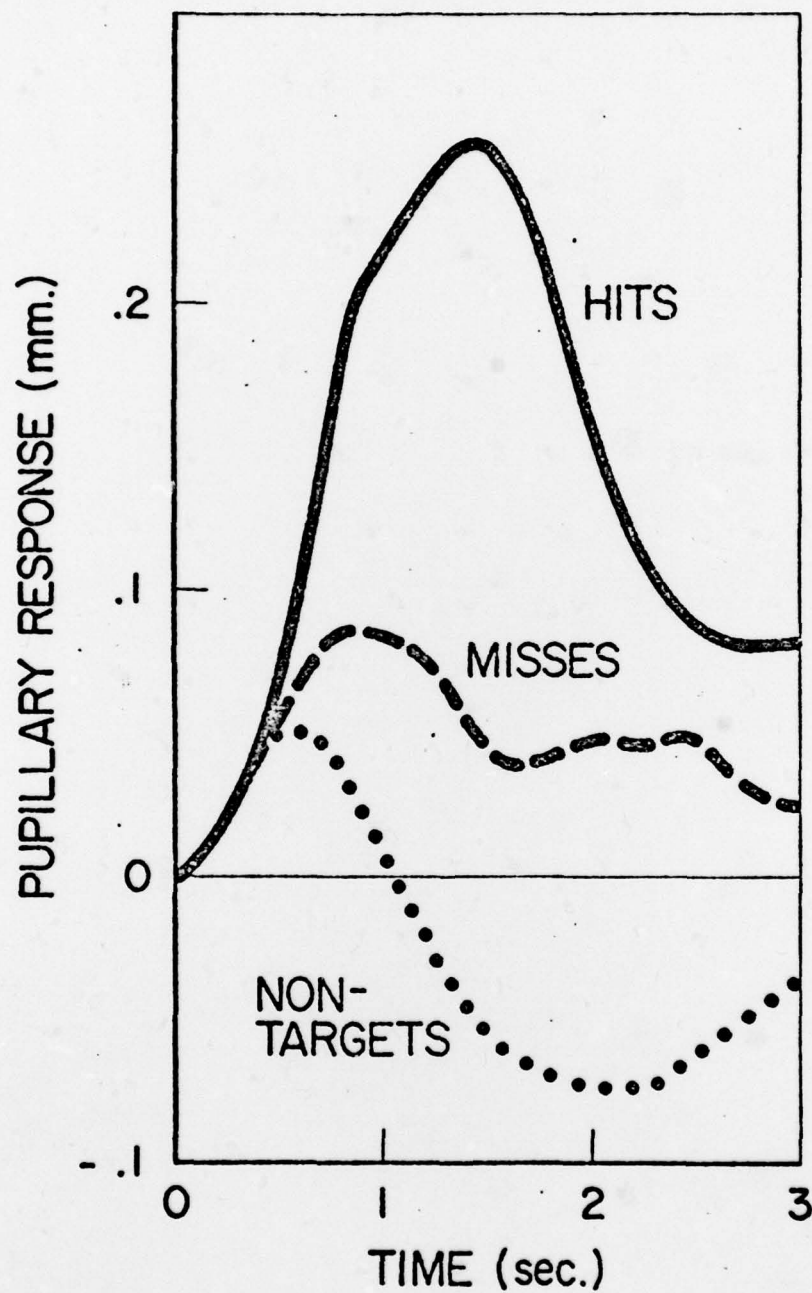


Figure 3. Averaged evoked pupillary response for nontarget stimuli, and for detected and undetected target stimuli.

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## DISCUSSION

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Although tonic pupillary diameter decreases markedly between wakefulness and the onset of sleep (Yoss, Moyer, & Hollenhorst, 1970) and decreases over an 8-hour work period (Lowenstein & Loewenfeld, 1952), the extent of that decrease being greater after subjectively more fatiguing work (Peavler, 1974), tonic pupillary diameter is not related to performance in the auditory vigilance task employed in this experiment. In contrast, the amplitude of the phasic pupillary response to task-related stimuli did decrease in a manner paralleling the performance decrement. Such pupillary changes have been previously shown to be systematically related to performance characteristics in a variety of information-processing tasks. In these contexts, pupillary dilations have been taken as a sign of attention (Beatty, 1977) or "effort" (Kahneman, 1973). The present experiment extends this relation to include vigilance tasks. These data suggest that the behavioral processes of both intensive and sustained attention might share a common physiological basis. However, the apparent dissociation between sustained attention and tonic arousal level deserves further explication.

Mention should also be made of the difference in the evoked pupillary response to targets that were detected and targets that were missed. Although the larger dilations observed in the former case might to some extent reflect differences in predecisional processing of the auditory signal, the fact that a behavioral response was required only for detected targets suggests a simpler alternative. The large magnitude dilations observed for detected targets probably reflects activation associated with response organization and execution (Kahneman, 1973). Similar response effects have been previously reported in other experimental tasks (Palvio, 1973).

The dissociation between phasic and tonic pupillometric measures of central nervous system activation observed in the present experiment indicates that a detailed analysis of the relations between activation and attention is necessary. One attempt in this direction has been published recently by Pribram and McGuinness (1975). The strength of the empirical relations between activation measures and performance variables observed here and elsewhere (Kahneman, 1973; Beatty, 1976, 1977) bode well for the ultimate success of an activation theory of attention.



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## REFERENCES

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- Beatty, J. Pupillometric measurement of cognitive workload. In Proceedings of the Twelfth Annual Conference on Manual Control (NASA TM X-73,170). Washington, D.C.: National Aeronautics and Space Administration, 1976.
- Beatty, J. Activation and attention. In M.C. Wittrock, J. Beatty, J.E. Bogen, M.S. Gazzaniga, H.J. Jerison, S.B. Krashen, R.D. Nebes & T. Teyler, The human brain. Englewood Cliffs, New Jersey: Prentice-Hall, 1977.
- Beatty, J., Greenberg, A., Deibler, W.P., & O'Hanlon, J.F. Operant control of occipital theta rhythm affects performance in a radar monitoring task. Science, 1974, 183, 871-873.
- Duffy, E. Activation. In N.S. Greenfield & R.A. Sternbach (Eds.), Handbook of psychophysiology. New York: Holt, Rinehart & Winston, 1972.
- Goldwater, B.C. Psychological significance of pupillary movements. Psychological Bulletin, 1972, 77, 340-355.
- Green, D.M., & Swets, J.A. Signal detection theory and psychophysics. New York: Wiley, 1966.
- Groll, E. Central nervous system and peripheral activation variables during vigilance performance. (In German, English summary). Zeitschrift fur Experimentelle und Angewandte Psychologie, 1966, 13, 248-264.
- Haider, M., Spong, P., & Lindsley, D.B. Attention, vigilance, and cortical evoked-potentials in humans. Science, 1964, 145, 180-182.
- Jerison, H.J. Vigilance: Biology, psychology, theory and practice. In R. Mackie (Ed.), Vigilance: Theory, operational performance, and physiological correlates. New York: Plenum, 1977.
- Kahneman, D. Attention and effort. Englewood Cliffs, New Jersey: Prentice-Hall, 1973.
- Kahneman, D., & Beatty, J. Pupil diameter and load on memory. Science, 1966, 154, 1583-1585.
- Kahneman, D., & Beatty, J. Pupillary responses in a pitch-discrimination task. Perception & Psychophysics, 1967, 2, 101-105.
- Loewenfeld, I.E. Mechanisms of reflex dilation of the pupil, historical and experimental analysis. Documenta Ophthalmologica, 1958, 12, 185-448.
- Lowenstein, O., & Lowenfeld, I.E. Disintegration of central autonomic regulation during fatigue and its reintegration by psychosensory controlling mechanisms. I. Disintegration. Pupillographic studies. Journal of Nervous and Mental Disease, 1952, 115, 1-21.

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- Mackie, R. (Ed.). Vigilance: Theory, operational performance, and physiological correlates. New York: Plenum, 1977.
- Mackworth, J.F. Vigilance and habituation. Baltimore: Penguin, 1969.
- Moruzzi, G. The sleep-waking cycle. Reviews of Physiology: Biochemistry and Experimental Pharmacology. New York: Springer-Verlag, 1972.
- O'Hanlon, J.F., & Beatty, J. Concurrence of electroencephalographic and performance changes during a simulated radar watch and some implications for the arousal theory of vigilance. In R. Mackie (Ed.), Vigilance: Theory, operational performance, and physiological correlates. New York: Plenum, 1977.
- Oswald, I. Sleeping and waking. New York: Elsevier, 1962.
- Paivio, A. Psychophysiological correlates of imagery. In F.J. McGuigan & R.A. Schoonover (Eds.), The psychophysiology of thinking. New York: Academic Press, 1973.
- Peavler, W.S. Individual differences in pupil size and performance. In M. Janisse (Ed.), Pupillary dynamics and behavior. New York: Plenum, 1974.
- Pribram, K.H., & McGuinness, D. Arousal, activation, and effort in the control of attention. Psychological Review, 1975, 82, 116-149.
- Rechtschaffen, A., & Kales, A. Manual of standardized terminology, techniques and scoring system for sleep stages of human subjects. USPHS. Washington, D.C.: U.S. Government Printing Office, 1968.
- Schlag, J. Reticular influences on thalamo-cortical activity. In O. Creutzfeldt (Ed.), Handbook of Electroencephalography and Clinical Neurophysiology. Volume 2: Electrical activity from the neuron to the EEG and EMG. Amsterdam: Elsevier, 1974.
- Stroh, C.M. Vigilance: The problem of sustained attention. Oxford: Pergamon Press, 1971.
- Williams, H.L., Granda, A.M., Jones, R.C., Lubin, A., & Armington, J.C. EEG frequency and finger pulse volume as predictors of reaction time during sleep loss. Electroencephalography and Clinical Neurophysiology, 1962, 14, 64-70.
- Yoss, R.E., Moyer, N.J., & Hollenhorst, R.W. Pupil size and spontaneous pupillary waves associated with alertness, drowsiness, and sleep. Neurology, 1970, 201, 545-554.
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